

Searches for the Higgs boson in Minimal Supersymmetric CP-conserving and CP-violating Standard Model scenarios at LEP

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It is important to study extended models containing more than one physical Higgs boson in the spectrum. In particular, Two Higgs Doublet Models (2HDMs)¹ are attractive extensions of the SM, predicting new phenomena with the fewest new parameters. The Higgs sector in the Minimal Supersymmetric extension of the SM (MSSM) is a 2HDM itself. The neutral Higgs searches performed at LEP are showing no evidence of the presence of a signal and have therefore been interpreted in the context of 2HDMs. Depending on the model considered exclusion of large regions of the parameter space can be obtained, but the existence of the lightest Higgs boson with masses lower than 90 GeV is not ruled out in all models by LEP. In the MSSM at least one of the neutral Higgs bosons is predicted to have its mass close to the electroweak energy scale; when radiative corrections are included², this mass should be less than about 140 GeV. This prediction provides a strong motivation for searches at present and future colliders.

1 Introduction

In the context of 2HDMs the Higgs sector comprises five physical Higgs bosons: two neutral CP-even scalars, h^0 and H^0 (with $m_h < m_H$), one CP-odd scalar, A^0 , and two charged scalars, H^\pm . Two Higgs Doublet Models are classified according to the Higgs boson couplings to fermions. In Type II models the first Higgs doublet couples only to down-type fermions and the second Higgs doublet couples only to up-type fermions. The Higgs sector in the minimal supersymmetric extension of the SM¹ is a Type II 2HDM, in which the introduction of supersymmetry adds new particles and constrains the parameter space of the Higgs sector of the model.

At the centre-of-mass energies accessed by LEP, the h^0 , H^0 and A^0 bosons are expected to be produced predominantly via two processes: the Higgsstrahlung process $e^+e^- \rightarrow h^0 Z^0$ or $e^+e^- \rightarrow H^0 Z^0$ and the pair-production process $e^+e^- \rightarrow h^0 A^0$.

In the MSSM, the Higgs potential is invariant under CP transformations at tree level. However it is possible to explicitly or spontaneously break CP symmetry by radiative corrections, in particular by contributions from third generation scalar-quarks³. The introduction of CP-violation is interesting since it provides a possible solution to the cosmic baryon asymmetry⁴, while the size of the CP-violating (CPV) effects occurring in the SM are far too small to account for it. Unlike the CP Conserving (CPC) case, in the CPV MSSM the Higgs mass eigenstates H_1, H_2 and H_3 are not CP eigenstates. This influences predominantly the couplings in the Higgs sector: the mass eigenstates are mixtures of the CP eigenstates h, H and A and since only the CP-even field component couples to the Z^0 boson, the individual couplings of the mass eigenstates are reduced in the CPV with respect to the CPC case.

The size of the CP-violation scales qualitatively as the fourth power of the top mass and as the imaginary part of the Higgs-squark trilinear coupling⁵.

2 Interpretation of the results

The four LEP collaborations have searched for neutral Higgses using all LEP2 data up to the highest LEP energy, $\sqrt{s}=209$ GeV. No evidence of an excess of events with respect to the SM expectation has been found⁶. The presence of neutral Higgs bosons is tested in the MSSM as well as in a general 2HDM(II). The MSSM model considered is a constrained MSSM with seven parameters which are not varied independently: only a certain number of “benchmark sets” are chosen where the tree level parameters $\tan\beta$ and m_A (CPC scenario) or m_{H^\pm} (CPV scenario) are scanned while all other parameters are fixed⁷.

2.1 The CPC MSSM

Three CPC benchmark scenarios have been studied. The *no-mixing* scenario where the stop mixing parameter X_t is set to zero, giving rise to a relatively restricted MSSM parameter space. The *m_h -max* scenario, designed to maximise the theoretical upper bound on m_h and the *large- μ* scenario, where the h^0 decays to $b\bar{b}$ are suppressed, on which most of the searches are based⁶. The *large- μ* scenario is nearly completely excluded due to the contribution of the so called “flavour-independent” searches that do not depend explicitly on b-tagging with the exception of one thin strip at large m_A and large $\tan\beta$ which is at the edge of being excluded at 95 % Confidence Level (CL). Figure 1.a) shows the exclusion in the $\tan\beta$ versus m_A projection in the *m_h -max* scenario. The obtained lower limit on the lightest Higgs boson mass is of 92.9 GeV and 93.3 GeV for the *m_h -max* and *no-mixing* scenarios, respectively, which, taking into account the upper theoretical bound², restricts the mass window where the lightest MSSM Higgs can be discovered to $93 \lesssim m_h \lesssim 140$ GeV.

New benchmarks have been designed, motivated either by the fact that the planned Higgs searches at LHC may have low sensitivity in those situations, or by experimental constraints on the branching ratio of the inclusive decay $b \rightarrow s\gamma$ and recent measurements of the muon anomalous magnetic moment $(g-2)_\mu$. An interpretation of the data of the four LEP experiments in those new benchmark scans is in preparation, but results by the OPAL collaboration are available⁸: the OPAL exclusion limits obtained from the new and the traditional scans are very similar, indicating that the LEP results for the new scans won’t change significantly the conclusions drawn previously.

At this point the question arises whether by looking closely at the LEP data there is some indication of the presence of a Higgs. Figure 1.b) shows the 1-CL_b confidence level, which is a measure of the overall agreement between the data and the Monte Carlo expectation in the absence of signal. The two largest deviations observed, for $m_h \sim 98$ GeV and $m_h \sim 115$ GeV, are barely exceeding two standard deviations. Recent attempts to explain those discrepancies as the

production of $h^0 Z^0$ and $H^0 Z^0$, respectively, have been made. Suitable choices of the parameters have been found in the context of general 2HDM, CPC or CPV MSSM^{9,5}, but it should be noted that the probability of such discrepancies to be caused by a background fluctuation is quite large.

2.2 The CPV MSSM

The interpretation of the LEP searches in the CPV MSSM has been performed in the context of a benchmark that maximises CPV⁷. Figure 2.a) shows the exclusion in the $\tan\beta$ versus m_{H^\pm} projection. In this scenario no lower limit on m_h can be extracted, mainly because of the reduced couplings of the lightest Higgs to the Z^0 boson⁶. A lower bound on $\tan\beta$ at 2.6 (2.7 expected) can be set in the assumption that $m_t = 179.3$ GeV.

2.3 The general 2HDM(II)

A scan of the general 2HDM(II) has been performed by the OPAL collaboration interpreting the same set of data used for the MSSM scans¹⁰. Figure 2.b) shows exclusion in the m_h versus m_A projection. As in the case of the CPV MSSM it is not possible to extract a lower limit on m_h or m_A given the generality of the model and the fact that the Higgs boson couplings to the Z^0 , as well as the branching ratio to $b\bar{b}$, can be strongly suppressed in large regions of the parameter space.

3 Conclusions

At LEP we have searched for Higgses in several extensions of the SM, in particular in the context of general 2HDM(II), CPC and CPV MSSM. No evidence of a signal has been found. In the CPC MSSM the mass window in which the lightest Higgs boson could still be found by future experiments is bounded from below at 90 GeV by the direct LEP searches and from above at about 140 GeV by theoretical constraints. In the CPV MSSM and in general 2HDMs no lower limit on the lightest Higgs boson mass can be extracted.

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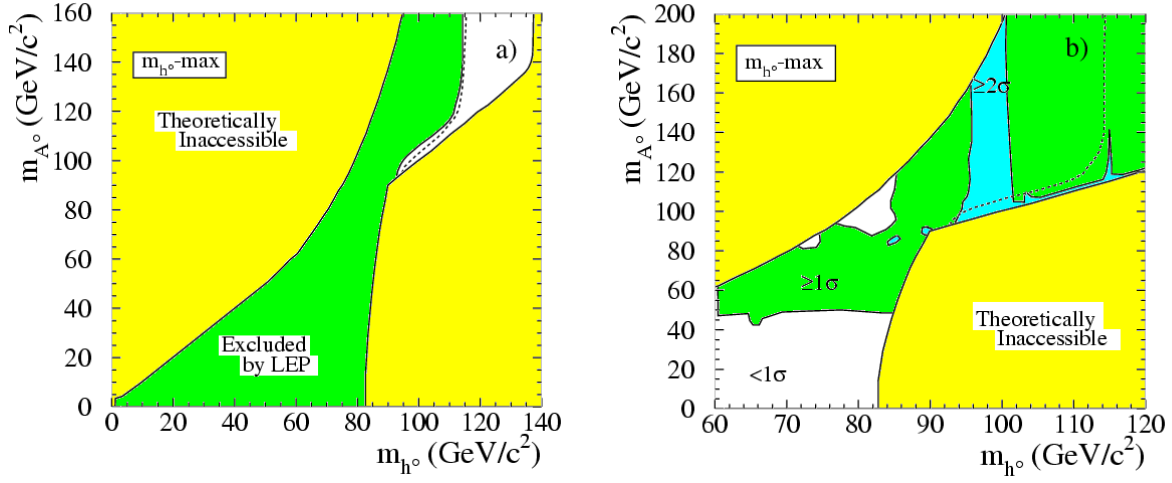


Figure 1: a) The 95 % CL exclusion (dark grey/green area) by LEP in the (m_A, m_h) plane, for the CPC MSSM m_h -max benchmark scenario, with $m_t = 179.3$ GeV. The dashed lines indicate the expected exclusion on the basis of Monte Carlo simulations with no signal. b) Contours of the $1 - CL_b$ confidence level for the m_h -max benchmark scenario, in the (m_h, m_A) projection of the MSSM parameter space. The theoretical limits are indicated. In the light-grey (blue) regions, labeled $\geq 2\sigma$, data deviate from Monte Carlo by about two to three standard deviations. The dashed line represents the upper edge of the region excluded at 95 % CL by this search.

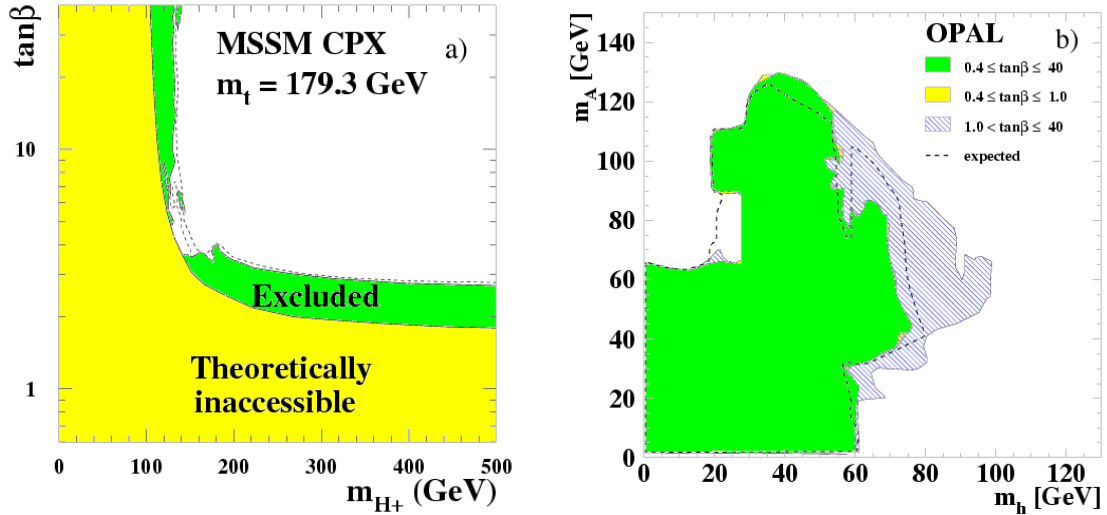


Figure 2: a) LEP exclusion at 95 % CL (dark grey/green area) in the $(m_{H+}, \tan\beta)$ projection, for the CPV MSSM benchmark scenario, with $m_t = 179.3$ GeV. The dashed lines indicate expected exclusion in case of the absence of signal. b) Observed (dark grey/green area) and expected (dashed line) excluded contours in the 2HDM(II) by the OPAL collaboration in the (m_A, m_h) projection. Observed exclusion for restricted $\tan\beta$ ranges ($0.4 \leq \tan\beta \leq 1.0$ and $1.0 \leq \tan\beta \leq 40$) are also shown.